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KNOW THE STAR, KNOW THE PLANET. I. ADAPTIVE OPTICS OF EXOPLANET HOST STARS

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ABSTRACT

The results of an adaptive optics survey of exoplanet host stars for stellar companions are presented. We used the Advanced Electro-Optical System telescope and its adaptive optics system to collect deep images of the stars in the *I* band. Sixty-two exoplanet host stars were observed and fifteen multiple star systems were resolved. Of these eight are known multiples, while seven are new candidate binaries. For all binaries, we measured the relative astrometry of the pair and the differential magnitude in the *I* band. We improved the orbits of HD 19994 and τ Boo. These observations will provide improved statistics on the duplicity of exoplanet host stars and provide an increased understanding of the dynamics of known binary star exoplanet hosts.

Key words: astrometry – binaries: close – binaries: visual – instrumentation: adaptive optics – planetary systems – techniques: photometric

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1. INTRODUCTION

There are a number of reasons to gain a better understanding of the binary fraction of exoplanet hosts. Binary stars influence the environment of the planet, both affecting where planets form and altering their orbits. Unseen binary stars complicate the analysis of exoplanets, and under some circumstances may masquerade as exoplanets themselves.

There are several proposed ways in which binary stars can influence the orbital properties of exoplanets. Binaries may interact with the protoplanetary disk from which planets form; for binary stars with separations less than 100 AU, interactions with the protoplanetary disk may lead to altered planet formation. If the protoplanetary disk surrounds the primary star, the tidal torques of the companion may lead to a truncation of the disk (Artymowicz & Lubow 1994). Eccentric companions can cause the disk to assume a similar shape, leading to a more eccentric orbit of the planet, which is then driven inward while accreting large amounts of gas (Kley & Nelson 2010). Kley & Nelson also suggest the companion may alter the planetesimal accretion rates in a disk with a close binary companion. Core accretion may have difficulties explaining planets orbiting one member of a close binary system; an example of this is the γ Cep system.

The problem with validating these theories and models is that we are unable to observe the process as it occurs. Instead, we are forced to work backward, using statistical analysis of duplicity fraction and orbital parameters to determine what happened. There have been several analyses of the statistics of binary stars. According to a study by Eggenberger et al. (2004), massive planets in close orbits are mostly found in binaries. They also noted other possible peculiar characteristics of planets in binaries: low eccentricities for orbital periods shorter than 40 days and a lack of massive planets with periods longer than 100 days in binaries. Within three years of their analysis, the number of planets in binaries increased from 19 planets in 15 multiple star systems to 40 planets in 38 multiple star systems. Desidera & Barbieri (2007) studied the distribution of eccentricity, mass, period, and metallicity of planets in this larger sample of binary systems. They found that the Eggenberger et al. (2004) suggestion that there was a lack of massive planets with periods >100 days in binaries was not valid. Instead, massive planets in short period orbits are found in most cases around the components of close binaries. Raghavan et al. (2006) carried out a comprehensive review of the literature and archival data to show that for 23% of radial velocity (RV) detected planets, the host star was a binary and that three planetary systems were in triple systems with the possibility that another two were also in triple systems.

Undetected binaries or even optical doubles can alter the analysis of exoplanets. For transiting exoplanets, the transit depth is assumed to be a percentage of a single star's brightness, but an undetected companion or nearby field star can affect the accuracy of the results. Correcting for this can change the derived planetary diameters by a few percent (Daemgen et al. 2009).

Exoplanet host stars are also prime targets for coronagraphic searches for additional exoplanets (e.g., Leconte et al. 2010). Identifying background stars and stellar companions assist those observations by eliminating the need to spend observing time establishing the true nature of each candidate planet.

Finally, some candidate exoplanets are actually stellar companions. This misidentification usually arises from RV observations, where the mass and semi-major axis results are projected onto the inclination of the orbit. A low-mass star in a nearly face-on orbit can masquerade as a massive planet in a higher-inclination orbit. This will probably be an increasing problem as the time baseline for RV searches increases. An example of such a masquerading star is HD 104304. Schnupp et al. (2010) used adaptive optics (AO) and "Lucky Imaging" to show that the substellar object orbiting this solar analog was actually an M4V star in a near face-on orbit. Another example is HD 8673, which is probably a K or an M star in a low inclination orbit (Mason et al. 2011).

It is essential to eliminate masquerading stars when analyzing the statistics of exoplanets because it prevents the unnecessary application of observing time and other resources toward better understanding an "exoplanet," when in actuality it is a star.

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It also offers an opportunity for stellar astronomy, in that it is possible to compute the masses of the individual stars by combining spectroscopic and astrometric orbital information. There are relatively few well-determined stellar masses and any opportunity to increase this number is valuable.

There have been a number of prior papers that studied duplicity rates among the exoplanet hosts. Patience et al. (2002) used near-IR speckle interferometry and AO to observe 11 exoplanet hosts and discovered one binary and collected astrometry on two known binaries. Southern exoplanet hosts were observed by Eggenberger et al. (2007) and in the 57 exoplanet hosts and 73 control stars they observed, they found 19 true companions, 2 likely bound objects, and 34 background stars. Another 40 candidate companions require additional data to determine if they are physical. Chauvin et al. (2006) used the Very Large Telescope (VLT) and the Canada–France–Hawaii Telescope (CFHT) to study 26 stars with planets and found 3 confirmed companions and 8 candidate companions, which also require follow-up observations. Mugrauer and colleagues have observed a number of stars in a large series of papers that cover the detection of a few binaries in each paper (e.g., Mugrauer et al. 2005, 2007; Neuhäuser et al. 2007).

With these thoughts, we started a survey of exoplanet hosts in 2001 with the Advanced Electro-Optical System (AEOS) telescope and its AO system. Section 2 discusses the observations and data reduction methodology. Results are discussed in Section 3. Subsections are dedicated to observations of new candidate companions, null detections, and the computation of orbits to previously known exoplanet host stars. Section 4 discusses archival observations from the Two Micron All Sky Survey (2MASS) and finally Section 5 summarizes our results.

2. DATA COLLECTION AND ANALYSIS

Observations were made using the AEOS 3.6m telescope and its AO system. The AEOS telescope is located at the Maui Space Surveillance System at the summit of Haleakala mountain. There were dedicated observing runs in 2001 February, 2001 September, 2002 March, and 2002 September. Stars were also observed on a queue scheduled basis between 2001 and 2005.

The AEOS AO system is a natural guide star system using a Shack–Hartmann wavefront sensor (Roberts & Neyman 2002). The individual subapertures have a diameter of 11.9 cm projected onto the primary. The deformable mirror has 941 actuators. The system's closed loop bandwidth is adjustable and can run up to 200 Hz, although the normal range is approximately 50 Hz. In the configuration used for these observations, the light from 500–540 nm is sent to the tip/tilt detector system, the light from 540–700 nm is sent to the wavefront sensor, and the light longer than 700 nm is sent to the Visible Imager CCD science camera. It operates from 700 to 1050 nm; is equipped with an atmospheric dispersion corrector; has a two-mode image derotator (zenith at a fixed position in the image or celestial north at a fixed position in the image); and, for this project, has a 10″ field of view (FOV; 0.″022 pixel^{-1}). The detector is a 512 × 512 pixel E2V CCD, with a read noise of 12 e^- rms. The camera output is digitized to 12 bits with 10 e^- per digital number.

The observing list was created by taking the list of known stars with known exoplanets as of early 2001 and then removing stars fainter than the effective magnitude limit of the AEOS AO system (about $m_v = 8$), and stars that were outside of the declination limit of acceptable AO correction (objects that at some time during the year get above 30° elevation at Haleakala, i.e., a declination greater than about −45°). In addition, we had an ongoing program to observe known binaries with the AEOS telescope (Roberts 2011). We compared the list of observed targets against the list of known exoplanet host stars to find targets that were not known to host an exoplanet at the time we observed them. This turned up several additional objects, which are included in this paper.

Each data set consists of 1000 frames obtained using a Bessel *I*-band filter ($\lambda_0 = 880$ nm). After collection, any saturated frames are discarded and the remaining frames are debiased, dark subtracted, and flat fielded. The frames are weighted by their peak pixel, which is proportional to their Strehl ratio and then co-added using a shift-and-add routine. The resulting image is analyzed with the program *fitstars*; it uses an iterative blind-deconvolution that fits the location of delta functions and their relative intensity to the data. The co-adding technique and the analysis with *fitstars* was presented in ten Brummelaar et al. (1996, 2000).

Error bars on the astrometry and photometry were assigned using the method described in Roberts et al. (2005). For the photometry, simulated binary stars were created from observations of single stars. The photometry of these simulated binaries was measured and used to create a grid of measurement errors as a function of separation and differential magnitudes. For astrometry, the separation error bar is ±0.″02 for $\rho \leqslant 1''$, ±0.″01 for $1'' < \rho \leqslant 4''$, and ±0.″02 for $\rho > 4''$. The position angle error bar is ±2° for $\rho < 1''$ and ±1° for $\rho > 1''$. The Visible Imager Data taken in 2001 did not record which state the derotator was in (either fixed north or fixed zenith). As such there is an ambiguity in the position angle for these measurements.

3. RESULTS

In Section 3.1, we discuss the observations of known binaries, while in Section 3.2 we discuss binaries detected for the first time. Finally, in Section 3.3, we discuss the stars where no companion was detected. The astrometry and photometry of all resolved systems are listed in Table 1.

For each star, we list the Washington Double Star (WDS) number, the discovery designation, the most common planet designation if it has one other than the HD number, the *Hipparcos* and HD catalog numbers, the Besselian date of the observation, the separation in arcseconds, the position angle in degrees, and finally the differential magnitude measured in the Bessel *I* band. The listed astrometry was compared with the latest published astrometry in the WDS. In some cases, this helped alleviate the derotator discrepancy between zenith mode and astronomical north mode and allowed us to determine the position angle. In all cases, our astrometry was consistent with previous results.

3.1. Known Binaries

HD 19994 (WDS 03128−0112). This system has a 1.68 M_J planet in a 535 ± 3.10 day period (Mayor et al. 2004). Its semi-major axis is 1.42 AU. We examined the previous orbit for this system (Hale 1994) and determined a new orbit was warranted. There is a large scatter in measured separation in the early measurements, which results in a poor solution. Convergence was achieved by fixing the eccentricity to a value minimizing the $O-C$ of measures and then allowing other parameters to vary. With all parameters floating, the orbit solution quickly

Table 1
Exoplanet Host Binaries

WDS	Discovery Designation	Planet	HIP	HD	Epoch	ρ ($''$)	θ (deg)	ΔI
02104−5049	ESG 1	GJ 86	10138	13445	2001.7454	1.70	114.8Z/112.1N	9.0 ± 0.8
02353−0334	MUG 2 AB	79 Cet	12048	16141	2001.7454	6.07	191.8Z/183.7N	5.64 ± 0.07
03128−0112	HJ 663	...	14954	19994	2002.6845	2.32	206.8	4.33 ± 0.02
05370+2044	RBR 15 AB	...	26381	37124	2003.9108	3.03	160.3	9.6 ± 0.7
05370+2044	RBR 15 AC	...	26381	37124	2003.9108	3.17	299.1	9.5 ± 0.7
07318+1705	RBR 16	...	36616	59686	2004.0477	5.61	224.8	4.60 ± 0.01
10222+4114	RBR 17 AH	...	50786	89744	2002.0166	5.62	26.6Z/53.6N	13 ± 2
13123+1731	PAT 47	...	64426	114762	2002.1069	3.27	26.9	9.2 ± 0.7
13284+1347	RBR 18 AD	70 Vir	65721	117176	2001.0994	2.86	191.3Z/241.2N	11.4 ± 1.2
13473+1727	STT 270	τ Boo	67275	120136	2001.0994	2.71	31.3	5.01 ± 0.04
16104+4349	RBR 19	14 Her	79248	145675	2002.2382	4.32	209.0	10.9 ± 1.0
19053+2555	EGN 24	...	93746	177830	2002.5474	1.62	84.1	7.5 ± 0.3
19418+5032	TRN 4Aa,Ab	16 Cyg	96895	186408	2002.5502	3.38	204.7	7.6 ± 0.3
					2002.6842	3.41	204.4	7.1 ± 0.3
19470+3425	RBR 20 AB	...	97336	187123	2002.5503	2.65	343.6	9.3 ± 0.7
19470+3425	RBR 20 AC	...	97336	187123	2002.5503	2.99	339.0	9.9 ± 0.7
19470+3425	RBR 20 AD	...	97336	187123	2002.5503	3.24	67.0	7.8 ± 0.3
					2002.6842	3.25	65.7	7.6 ± 0.3
19470+3425	RBR 20 AE	...	97336	187123	2002.5503	5.77	187.7	10.5 ± 1.0
20283+1846	HO 131AB	...	100970	195019	2002.4902	3.53	331.3	3.23 ± 0.01
22575+2046	RBR 21	51 Peg	113357	217014	2001.7340	2.87	154.5Z/244.9N	10.0 ± 0.7

Table 2
Orbital Elements

HD	Planet	Discoverer Designation	P (yr)	a ($''$)	i (deg)	Ω (deg)	T_0 (yr)	e	ω (deg)
19994	...	HJ 663	2029	9.87	104	97	2283	0.26	342
120136	τ Boo	STT 270	996	8.01	49	174	2035	0.76	322

Table 3
Orbital Ephemerides

WDS Designation	Planet	Discoverer Designation	2015.0 θ (deg)	2015.0 ρ ($''$)	2020.0 θ (deg)	2020.0 ρ ($''$)	2025.0 θ (deg)	2025.0 ρ ($''$)	2030.0 θ (deg)	2030.0 ρ ($''$)	2035.0 θ (deg)	2035.0 ρ ($''$)
03182−0112	HD 19994	HJ 663	196.4	2.178	192.0	2.147	187.4	2.129	182.8	2.123	178.2	2.131
13473+1727	τ Boo	STT 270	62.6	1.774	80.8	1.540	103.3	1.446	126.2	1.514	145.5	1.697

diverged with extremely high eccentricity. It is possible that the B companion is not physical and that early measures indicating curvilinear motion are measures with higher error to a linear fit. At present, there is no differential proper motion of the B component to confirm or deny this supposition. The orbit solution, an improvement on the solution of Hale (1994), should still be judged as preliminary. The elements of the orbit are shown in Table 2, while a plot of the orbit is shown in Figure 1. The predicted orbital positions until 2035 are shown in Table 3. The parallax of 44.29 mas (van Leeuwen 2007) implies a mass sum of 2.6 $M_{\odot}$, which is high for the estimated spectral types of the components of F8V and M3V (Hale 1994). The spectral type estimates would suggest a mass sum of 1.6 $M_{\odot}$. The mass sum from the Hale (1994) orbit is 1.8 $M_{\odot}$.

Combining the orbital elements with the parallax, we compute a separation of the two stars at periastron passage of 163 AU. This is a large enough separation that the companion probably has little or no impact on the planet itself, but if the planet scattered large numbers of planetesimals as it migrated, these planetesimals would then be scattered again by the stellar companion. This would certainly modify or possibly eliminate an outer debris disk analogous to the Kuiper Belt. No debris disk was detected by Dodson-Robinson et al. (2011).

τ Boo (HD 120136, WDS 13473+1727). This system hosts a massive planet in a 3.3128 day orbit (Butler et al. 1997) with a semi-major axis of 0.042 AU. There have been two previous orbits computed for this system, by Hale (1994) and Popovic & Pavlovic (1996). We computed a new solution, as shown in Figure 2; elements are listed in Table 2. The predicted orbital positions until 2035 are shown in Table 3.

The parallax of 64.03 mas (van Leeuwen 2007) implies a mass sum of 2.0 $M_{\odot}$. Hale's orbit gives 2.8 $M_{\odot}$, while that of Popovic & Pavlovic gives 6.3 $M_{\odot}$. The estimated spectral types from Hale (1994), F6IV and M2V, result in a mass sum of 1.8 $M_{\odot}$, within 10% of our estimate. While our orbit fits the early micrometry data better than the Popovic orbit, and the later AO and speckle interferometry data better than the Hale orbit, it warrants further refinement, which requires additional observations. Although it is moving faster and approaching periastron, given the orbital period, these additional observations will need to be several years in the future.

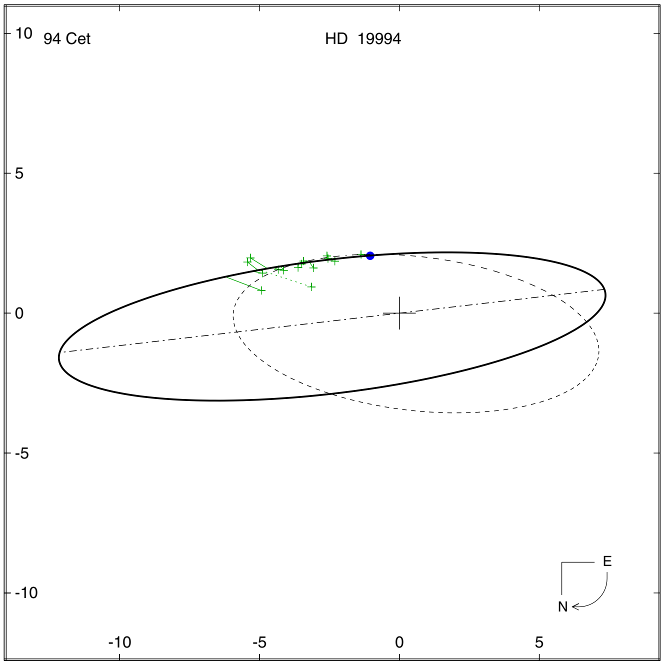

Figure 1. New orbit for the binary star HD 19994. The orbit with dashed lines is that of Hale (1994). The broken line through the origin is the line of nodes. The scale of the orbit in arcseconds is given at left and bottom and the orientation and direction of motion is at lower right. The "+" signs are historic filar micrometry measures and the filled circle is the new AO measure listed in Table 1. Measures are connected to the new orbit by $O-C$ lines.

(A color version of this figure is available in the online journal.)

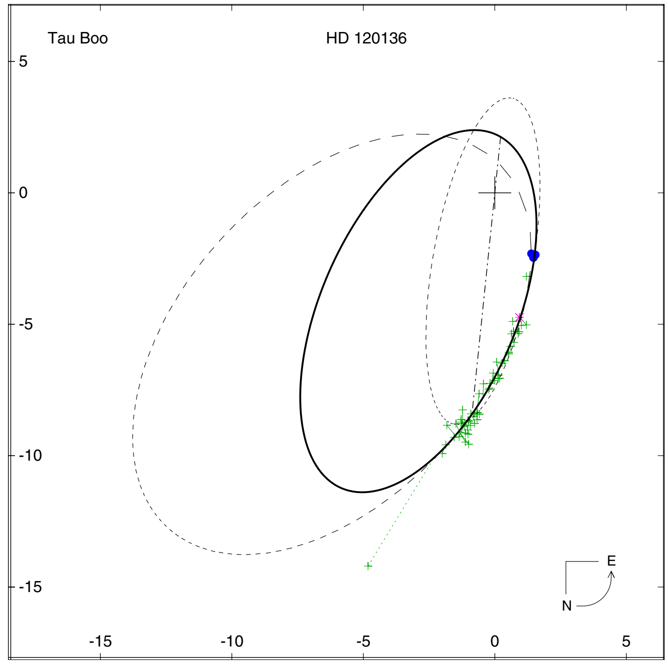

Figure 2. New orbit for the stellar companion to τ Boo. The orbit with long dashed lines is that of Hale (1994), while the orbit with the short dashed lines is the orbit of Popovic & Pavlovic (1996). The "+" signs are historic filar micrometry measures and the filled circles are modern speckle interferometry and AO measurements.

(A color version of this figure is available in the online journal.)

Combining the orbital elements with the parallax, we compute the separation of the two stars at periastron passage as 30.0 AU. If we assume the binary orbit has not altered through a close stellar encounter, since the formation of the planetary system, the minimum separation has a significant impact on the formation of the planet. This seems like a perfect example of what (Kley & Nelson 2010) proposed; eccentric stellar companions can cause the protoplanetary disk to become more eccentric, which leads to a more eccentric orbit for the planet. The planet is then driven inward, while accreting large amounts of gas, producing a massive planet. In this case, the planet's orbit was probably then tidally circularized. Planetary migration may explain why τ Boo only has a single massive planet in a very close orbit, as other proto-planets would have been scattered out of the disk. To determine the validity of this idea, detailed numerical simulations will be needed. A more refined orbit will also be useful, which requires additional astrometric measurements.

3.2. New Discoveries

HD 59686. We detected a candidate companion with a separation 5″.61 and a ΔI of 4.6. Based on the measured separation and the parallax of the star (van Leeuwen 2007) and assuming a face-on orbit with an inclination of zero, the candidate companion would have a minimum separation of 519 AU.

HD 89744. A faint candidate companion was detected with a separation of 5″.62 and a ΔI of 13 ± 2. Based on the spectral type of the primary (Montes et al. 2001), the differential magnitude of the companion would make it a brown dwarf. The star already has one low-mass stellar or high-mass brown dwarf companion detected (Mugrauer et al. 2004). That paper also detected several background or foreground objects that did not share common proper motion with HD 89744. Both our and Mugrauer et al.'s (2004) observations were made in 2002, so it is doubtful that the object we have detected is one of the background or foreground objects as they do appear to have similar astrometry. Mugrauer et al. (2004) did not detect our candidate companion, but their observations were not made with AO and probably did not have the dynamic range to detect it. Follow-up observations with near-IR AO are needed to make a final determination of whether our object is a true companion, an artifact or a background object. Again, assuming a face-on orbit, based on the measured separation and the parallax of the star (van Leeuwen 2007), the candidate companion would have a minimum separation of 219 AU.

70 Vir (HD 117176). Patience et al. (2002) did not find a companion to this star in their infrared survey. That may indicate that this is a false detection, that it is background blue star, or that the orbital position has changed. Based on the spectral type of the primary (Cowley et al. 1967), the absolute magnitudes of the Morgan–Keenan (MK) classification in Cox (2000), and the measured differential magnitude of 11.4 ± 1.2 the companion would be later than M5V, assuming it is on the main sequence. Due to its relatively high proper motion (van Leeuwen 2007), an additional observation at a current epoch will be able to determine whether the companion shares common proper motion or is a background object. Using the same assumptions as above, the candidate companion would have a minimum separation of 52 AU.

14 Her (HD 145675). Based on the spectral type of the primary (Montes et al. 2001), the absolute magnitudes of the MK classification in Cox (2000), and the measured differential magnitude of 10.9 ± 1.0, the companion would be later than M5V, assuming it is on the main sequence. Using the same

assumptions as above, the candidate companion would have a minimum separation of 78 AU.

HD 187123. Four possible candidates were detected in two images. The first image showed four candidate companions, while the second observation a month later showed only the brightest of these possible companions. The second observation had poorer AO correction, which offers a probable explanation for the failure to detect the other candidates. Based on the spectral type of the primary (Gray et al. 2001), the absolute magnitudes of the MK classification in Cox (2000), and the measured differential magnitudes, all three companions would be later than M5V, assuming they are on the main sequence. Based on the measured separations and the parallax of the star (van Leeuwen 2007), the candidate companions would have separations of 127 AU, 143 AU, 155 AU, and 276 AU. The system does not appear to form a hierarchical system, and it is highly likely that some or all of the companions are background objects.

51 Peg (HD 217014). Using the same assumptions as above, the candidate companion would have a separation of 45 AU. Due to its relatively high proper motion (van Leeuwen 2007), an additional observation at a current epoch will be able to determine whether the star has common proper motion or is a background object.

3.3. Single Stars

Table 4 lists the stars where no companions were detected. The table lists the WDS number of the system if there is one, HD and *Hipparcos* catalog numbers, the observation date, and the FWHM of the star. This provides a useful gauge for estimating the minimum separation resolvable by the observations and also provides a metric of AO performance. The AO performance varies from night to night, as a function of atmospheric conditions, target brightness, and air mass.

In order to quantify the sensitivity of the reduced images, we have created a variation of the "dynamic range map" technique described in Hinkley et al. (2007), which defines the dynamic range of a given position in a two-dimensional image as the faintest companion detectable at that position to the 5σ level. In our version, we construct a map the same size as each reduced image. The intensity level of each pixel in the map is set to five times the rms intensity variation across a patch centered on the corresponding pixel in the original image. The patch is a square with lengths equal to the FWHM of the original image. This produces the dynamic range map in intensity terms, which are then converted to magnitudes.

Figure 3 shows the results of this technique applied to the image of HD 8574 and is characteristic of the achievable dynamic range. It is apparent from the sample figure that the detection threshold for a companion is highly spatially variant. The dynamic range increases with increasing radius from the central star. There are several artifacts in this image which lower the dynamic range. The largest is the vertical line, which is an artifact of the shutter-less frame-transfer process. There is also the diffraction pattern caused by the secondary mirror support spiders.

As the AO system performance decreases, the FWHM of the point-spread function (PSF) will increase, which increases the area over which the central PSF causes confusion. In addition, it also widens the companions PSF, lowering the contrast between the two, and decreasing the detection rate.

Table 4
Unresolved Stars

WDS	Planet	HD	HIP	Epoch	FWHM ($''$)
...	...	6434	5054	2001.7453	0.14
...	...	8574	6643	2003.6891	0.08
...	ν And	9826	7513	2001.7370	0.14
...				2001.7452	0.12
...	109 Psc	10697	8159	2001.7452	0.11
	...	12661	9683	2001.7453	0.13
...	ι Her	17051	12653	2001.7454	0.12
	...	23596	17747	2003.7196	0.32
03329−0927	ϵ Eri	22049	16537	2003.7058	0.08
				2005.6471	0.12
				2005.6553	0.14
				2005.7837	0.14
				2005.7864	0.14
...	...	28185	20723	2003.7169	0.23
...	...	33636	24205	2003.7360	0.12
...	...	38529	27253	2001.8987	0.17
...	...	40979	28767	2003.9740	0.18
				2003.9796	0.12
06332+0528	...	46375	31246	2004.0445	0.13
...	...	49674	32916	2004.0860	0.27
...	...	52265	33719	2004.0477	0.14
...	...	68988	40687	2004.1299	0.16
...	...	72659	42030	2004.1218	0.30
...	...	74156	42723	2003.0074	0.08
				2004.1216	0.33
...	...	75289	43177	2004.0313	0.39
...	55 Cnc	75732	43587	2002.0903	0.12
...	...	82943	47007	2001.9811	0.22
				2002.1342	0.17
...	...	92788	52409	2002.0194	0.19
...	47 UMa	95128	53721	2001.9865	0.12
...	...	106252	59610	2003.2620	0.19
...	...	114729	64459	2003.2703	0.67
...	...	114783	64457	2003.2703	0.38
...	...	128311	71395	2003.3358	0.17
...	23 Lib	134987	74500	2002.1069	0.17
15249+5858	ι Dra	137759	75458	2003.3221	0.08
...	...	141937	77740	2004.2560	0.12
16010+3318	...	143761	78459	2003.3169	0.24
...	...	147513	80337	2003.5108	0.23
...	...	150706	80902	2003.4945	0.38
	μ Ara	160691	86796	2002.3177	0.21
...	...	168443	89844	2002.4954	0.22
...	...	168746	90004	2002.5446	0.41
...	...	169830	90485	2002.5446	0.12
				2002.6785	0.12
...	...	179949	94645	2002.5501	0.12
...	...	190228	98714	2003.5249	0.12
20036+2954	GJ 777A	190360	98767	2002.6842	0.18
...	...	192263	99711	2002.5721	0.12
...	...	202206	104903	2002.5666	0.17
...	...	209458	108859	2002.5556	0.21
				2002.6732	0.12
...	...	210277	109378	2002.5558	0.17
				2002.6843	0.22
22583−0224	...	217107	113421	2001.7370	0.19
23393+7738	γ Cep	222404	116727	2001.4963	0.10
23419−0559	...	222582	116906	2001.8653	0.39

These maps have several purposes. For those objects with multiple observations where companions are seen in some but not all of the data, changes in the dynamic range can help explain the reasons for these discrepancies and can put constraints on

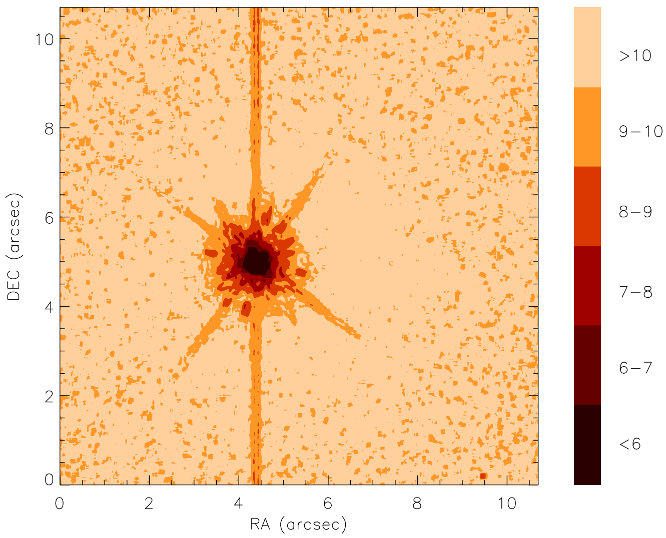

Figure 3. Sample dynamic range map of HD 8574. The gradient map on the right shows the 5σ detection limit for a given pixel of the image in magnitudes. (A color version of this figure is available in the online journal.)

the orbital solution (Hinkley et al. 2011). They also illustrate the limitations of the data, showing where it is almost impossible to find faint companions.

3.4. *Unresolved Binary Stars*

In this section, we discuss two binary stars that, based upon the published astrometry, we should have been able to resolve but did not. There are other binary stars listed in Table 4, but their published separations are either outside of the FOV, or are smaller than the PSF FWHM of the observation. The minimum separation in Table 4 and the widest routinely measurable separation of 5″ gives a useful "face-on donut" of non-detection.

HD 217107 (WDS 22583−0224, CHR 116). CHR 116 has only been resolved twice: in 1982 and in 1997. In the 15 years between, the separation changed from 0.″473 to 0.″274. It is quite likely that in the four years between the last measurement and our measurement, orbital motion has moved the companion to within the 0.″19 measured FWHM of the image. Examining the image, we do see a slight elongation of the PSF in one direction. It is possible that this is caused by the secondary. With a FWHM of 0.″19, the AO correction was not very good.

γ Cep (HD 222404, WDS 23393+7738, NHR 9). We did not detect the stellar companion seen by Neuhäuser et al. (2007). According to the orbit of Torres (2007), the companion would have a separation of 0.″17. As shown in Figure 3, it would be extremely difficult to detect a companion with the expected dynamic range at that separation.

4. 2MASS ANALYSIS

A check was made against the 2MASS Point Source Catalog (Skrutskie et al. 2006), looking for all objects within 10″ of the target stars as discussed in Turner et al. (2008). Only three such possible companions were found, all of which are previously known. The candidate companions to HD 114729 and HD 168746 are outside of our FOV.

79 Cet. A companion was found at 187.°5 and 5.″70, with ΔJ = 3.59. Mugrauer et al. (2005) detected this companion with AO in 2002 and noted the match with the 2MASS object.

HD 114729. This object is listed as a single star in Table 4. A possible companion was found in the 2MASS database, but with a separation of about 8″, this object falls outside the observing window of the VisIm detector, and we did not detect it.

HD 168746. This star is also listed as single in Table 4. A possible companion was found in the 2MASS database with a separation of 9″, it is well outside our observing window and was not detected.

5. SUMMARY

We observed 62 exoplanet host stars with the AEOS AO system, and resolved 15 multiple star systems. Of these, eight are known multiples, while seven are new candidate binaries. Additional observations are needed to determine whether these are true binaries or merely optical doubles. We computed updated orbits of HD 19994 and τ Boo. Both are improved from the previous orbit, but require additional observations to further refine these solutions. Both orbits show that the presence of a binary companion can affect the structure of the planetary system. In the case of HD 19994, the companion may have disrupted any Kuiper Belt analogs. The τ Boo stellar companion may have altered the protoplanetary disk and caused only a single massive planet to form at a very small separation. In this way, determining the orbits of binary star companions to exoplanet hosts may shed new light on the formation of the exoplanets.

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REFERENCES

Artymowicz, P., & Lubow, S. H. 1994, ApJ, 421, 651
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Chauvin, G., Lagrange, A.-M., Udry, S., et al. 2006, A&A, 456, 1165
Cowley, A. P., Hiltner, W. A., & Witt, A. N. 1967, AJ, 72, 1334
Cox, A. N. 2000, Allen's Astrophysical Quantities (New York: Springer)
Daemgen, S., Hormuth, F., Brandner, W., et al. 2009, A&A, 498, 567
Desidera, S., & Barbieri, M. 2007, A&A, 462, 345
Dodson-Robinson, S. E., Beichman, C. A., Carpenter, J. M., & Bryden, G. 2011, AJ, 141, 11
Eggenberger, A., Udry, S., Chauvin, G., et al. 2007, A&A, 474, 273

Eggenberger, P., Udry, S., & Mayor, M. 2004, A&A, 422, 247
Gray, R. O., Napier, M. G., & Winkler, L. I. 2001, AJ, 121, 2148
Hale, A. 1994, AJ, 107, 306
Hinkley, S., Monnier, J. D., Oppenheimer, B. R., et al. 2011, ApJ, 726, 104
Hinkley, S., Oppenheimer, B. R., Soummer, R., et al. 2007, ApJ, 654, 633
Kley, W., & Nelson, R. P. 2010, Planets in Binary Star Systems (New York: Springer)
Leconte, J., Soummer, R., Hinkley, S., et al. 2010, ApJ, 716, 1551
Mason, B. D., Hartkopf, W. I., Raghavan, D., et al. 2011, AJ, 142, 176
Mayor, M., Udry, S., Naef, D., et al. 2004, A&A, 415, 391
Montes, D., Lopez-Santiago, J., Galvez, M. C., et al. 2001, MNRAS, 328, 45
Mugrauer, M., Neuhäuser, R., & Mazeh, T. 2007, A&A, 469, 755
Mugrauer, M., Neuhäuser, R., Mazeh, T., Guenther, E., & Fernández, M. 2004, Astron. Nachr., 325, 718
Mugrauer, M., Neuhäuser, R., Seifahrt, A., Mazeh, T., & Guenther, E. 2005, A&A, 440, 1051
Neuhäuser, R., Mugrauer, M., Fukagawa, M., Torres, G., & Schmidt, T. 2007, A&A, 462, 777
Patience, J., White, R. J., Ghez, A. M., et al. 2002, ApJ, 581, 654
Popovic, G. M., & Pavlovic, R. 1996, Bull. Astron. Belgrade, 153, 57
Raghavan, D., Henry, T. J., Mason, B. D., et al. 2006, ApJ, 646, 523
Roberts, L. C., Jr. 2011, MNRAS, 413, 1200
Roberts, L. C., Jr., & Neyman, C. R. 2002, PASP, 114, 1260
Roberts, L. C., Jr., Turner, N. H., Bradford, L. H., et al. 2005, AJ, 130, 2262
Schnupp, C., Bergfors, C., Brandner, W., et al. 2010, A&A, 516, A21
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
ten Brummelaar, T. A., Mason, B. D., Bagnuolo, W. G., Jr., et al. 1996, AJ, 112, 1180
ten Brummelaar, T. A., Mason, B. D., McAlister, H. A., et al. 2000, AJ, 119, 2403
Torres, G. 2007, ApJ, 654, 1095
Turner, N. H., ten Brummelaar, T. A., Roberts, L. C., Jr., et al. 2008, AJ, 136, 554
van Leeuwen, F. 2007, A&A, 474, 653